IIigl]-1'recision Magellan Orbit Determination for Stereo Image Processing

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Introduction

From September 1990 until September 1992, the Magellan spacecraft observed the surface of Venus, using Synthetic Aperture Radar (SAR). During that time the spacecraft's ground track swept across Venus three times, as the planet completed three 243-day rotations, referred to as a "cycles". The SAR was operated differently cm each of the three cycles, in order to maximize the science return. The goal of the first cycle was to image as much of the surface as possible using a "left-looking" mode (i. e., the radar was boresighted to the left of the ground track as seen by an observer facing in the direction of the motion). During the second cycle, the radar was operated predominantly in a right-looking mode. In the third cycle, the radar was again used in a left-looking mode, but at a different off-nadir angle than in cycle 1. Because the incidence angle of the radar at the surface was 10°-200 different between cycles 1 and 3, overlapping images from the two cycles can be combined to produce stereo images and high-resolution digital elevation maps (DEMs) of the surface.

The processing of the radar echo data into images requires knowledge of the spacecraft's orbit. This orbit knowledge can be obtained to sufficient precision from Ilarth-based Doppler tracking measurements. I lowever, when radar images from multiple orbits are combined into mosaics necessary for geological mapping, typical relative errors between orbit solutions become evident as discontinuities running through the images. Relative errors in orbit solutions cause even larger artifacts in stereo products because stereo processing is particularly sensitive to ephemeris errors.

The purpose of this paper is to describe a technique which improves the precision of Magellan orbit determination by incorporating measurements of landmarks visible in the radar images. The basic technique was described in the Reference, but it has since been refined and significantly extended to handle multiple orbit solutions simultaneously. The new technique is particularly appropriate for stereo processing because it can greatly reduce relative errors between cycle 1 orbit solutions and cycle 3 orbit solutions.

Baseline Magellan Orbit Determination

The baseline technique for determining Magellan's orbit uses Earth-based Doppler measurements of the spacecraft velocity acquired during the periods when the spacecraft antenna is pointed at the Earth. The spacecraft position can be determined using these measurements to an absolute accuracy, relative to the center of Venus, of about 10 km, and a relative orbit-to-orbit accuracy of about 1 km. Although this level of accuracy is adequate for processing the radar data, it is not sufficient to eliminate artifacts in image mosaics and stereo products. For example, a 1-km along-track relative error between consecutive orbits causes a noticeable discontinuity in an image mosaic.

Relative orbit-to-orbit ephemeris errors arc largest across so-called "navigation boundaries", i.e., the boundaries between the blocks of 7-8 orbits covered by each navigation solution. The spacecraft ephemeris within each block (or "arc") is computed via a single continuous numerical integration of the equations of motion, and is based on a single set of tracking observations. Relative ephemeris errors across navigation boundaries arc larger than those within a navigation solution because the ephemerides arc computed from different numerical integrations and are based on different sets of tracking observations.

The Magellan Radar System and Stereo Processing of SAR Images

During each mapping pass, the Magellan radar observed a long narrow North-South swath of surface. The basic image is typically about 300 pixels wide by about **200,000** long, where the pixel size is 75 **m.** Series of'image swaths were mosaicked together at selected latitudes. These mosaics are 7168 by 8192 pixels in size and subtend an area of surface about S^0 cm a side. The number of orbits of data used in a mosaic varies from about 30 at the equat or to over 160 near the poles. Because they are comprised of so many orbits of data, mosaics contain many navigation boundaries, and therefore many opportunities for relative errors to produce artifacts.

Mosaics from cycles 1 and 3 of the same area of surface are combined using stereo algorit Inns to obtain high-resolution DEMs. St erco processing is very sensitive to ephemeris errors: even small errors lead to noticeable artifacts. The attached Figure illustrates this problem. It shows a small region near Maxwell Montes on Venus where stereo processing has been applied using the standard Earth-based ephemeris. The vertical bands measure the along-track shifts required to align sections of the images. For example, the vertical boundary down the center of the image is caused by a relative along-track error of about 700 m between two cycle 1 navigation solutions. Typical relative cross-track errors in the Earth-based ephemeris produce artificial "cliffs" up to a kilometer high running down the lengths of the DEMs. These artifacts cannot simply be removed comet i call y from the st creo products -- improving the accuracy of the spacecraft ephemeris is the best solution to the problem.

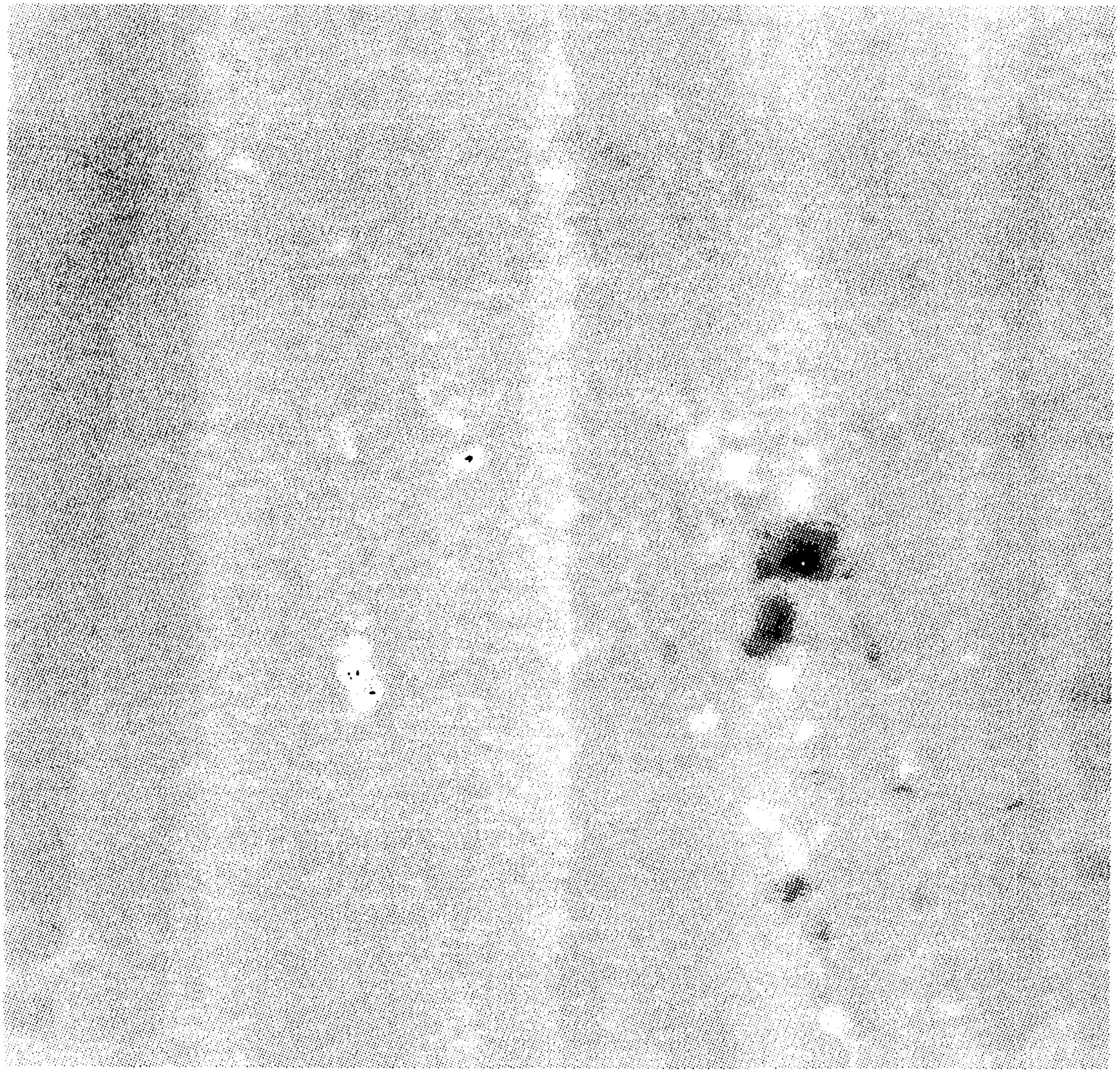
Magellan Orbit Determination Using SAR Landmark Measurements

The fact that ephemeris errors are noticeable in radar mosaics indicates that SAR imagery has high enough resolution to contribute orbit information. Measurements of distinct features ("landmarks") in Magellan radar images provide a means for improving the accuracy of the spacecraft's ephemeris. A method has been developed to combine landmark measurements with the standard data set of ground-based Doppler measurements to compute an improved spacecraft ephemeris (see Reference), The technique has been demonstrated to significantly improve the accuracy of the orbit estimate. The landmarks provide Venus-relative information which helps to tie one orbit to the next and reduce relative ephemeris errors.

The method described in the reference applied only to individual orbit-determination arcs, in this paper, the technique is extended to multiple arcs, where measurements of landmarks common to multiple arcs are used to tic the arcs together; i.e., the orbit solutions for the arcs are allowed to vary independently, but they are constrained by measurements of common landmarks. Alt bough this method is useful for tying together long series of consecutive arcs, it is especially appropriate for computing ephemerides for stereo processing. in the example to be described in the paper, the technique was applied to 7 arcs, 3 from cycle 1 and 4 from cycle 3 that covered much of the same terrain. Landmarks measured on two or more arcs served to reduce the relative errors not only between arcs on the same cycle, but also between cycle 1 arcs ant] cycle 3 arcs. The high precision of the resulting ephemeris led to a more accurate and artifact-free DEM.

Reference:

Chodas, P. W., T-C. Wang, W.L. Sjogren, and J.E. Ekelund, "Magellan Ephemeris Improvement Using Synthetic Apertu re Radar Landmark Measurements", Paper A AS 91-391, AAS/AIAA Ast rodynamics Conference, Durango, Colorado, August 19-22, 1991,



<---> CYCLE 3 NAVIGATION SOLUTION

<---> CYCLE 1 NAVIGATION SOLUTION

Relative Along-Track **Pixel Shifts** Between Mosaics **from** Cycle 1 and Cycle 3 **Showing the Boundaries** Between Navigation Solutions